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A Robust Adaptive Nonlinear Control Approach to Ship Straight-path Tracking Design

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Abstract— **This article focuses on the straight-path tracking problem for underactuated ships with parametric uncertainties and completely unknown control gain coefficient under bounded exogenous disturbances. Combined Nussbaum gain technique with backstepping approach, an adaptive robust controller is developed such that all signals and states are globally uniformly ultimately bounded (GUUB). Consequently, an underactuated ship can be stabilized on a prescribed straight path in a GUUB manner under external disturbances induced by wave and wind. Numerical simulation results on an ocean-going training ship 'YULONG', belonging to Dalian Maritime University, are presented to validate the effectiveness of the proposed algorithm.**

I. INTRODUCTION

In practice, long distance navigation tasks are frequently carried out while travelling via waypoints at constant cruise speed. To save travelling time, distance and fuel, ship straight-path tracking is an important practice and has received considerable attention([1]). When the linear course is to be tracked, only the yaw moment, supplied by the ship rudder control system, is served as control input to drive the sway displacement, sway velocity and heading angle to zero while the sway axis is not actuated, and the surge velocity is maintained by the main thruster control system. This configuration is by far the most common among marine surface vessels. So the goal of waypoint tracking is to control both the heading angle and the sway displacement by using the yaw torque only. The main difficulty of the problem is due to the underactuated nature of ships, especially in the presence of external disturbances.

In literature, several methods have been proposed. In [2], an input-output linearization based on output redefinition approach and sliding mode control was used to achieve asymptotic stability. But the convergence of the combined variable does not guarantee the convergence of its components. In [3], base on feedback linearization and backstepping technique, a control algorithm on a fourth-order ship model was developed with an estimation of the uncertain ocean current disturbance to track both line and circumference. A time-invariant global solution to the two degrees of freedom of stabilizing the kinematic model of an underactuated ship on a straight line is proposed in [4], but the external perturbations are not explicitly considered. In [5], a full state feedback control law is proposed using a cascaded approach to achieve globally asymptotical result on waypoint tracking control, the effect of external disturbance was not involved, too. Recently, combined the backstepping technique [6] and the Lyapunov direct approach, both a state and an output feedback controllers were developed in [7], which can force an underactuated ship to globally ultimately track a straight line under non-vanishing disturbances induced by wave, wind and ocean current. However, in most of these works, both the parameter uncertainties and external perturbations were seldom involved, especially with respect to the virtual control gain coefficients.

In this paper, we consider ship straight-line tracking control system with the parametric uncertainties and bounded disturbances , as well as the unknown control gain coefficient without a priori knowledge of its sign. Inspired by [8]-[10], an robust adaptive controller is explored based on the backstepping approach and Nussbaum gain technique([11]), such that all signals and states in the closed-loop system are globally uniformly ultimately bounded (GUUB), and that the system output, which is redefined as a combination of the sway displacement and heading angle, together with its components can be made converge to a small neighborhood of the origin as small as desired by an appropriate choice of the design parameters. Consequently, globally robust adaptive waypoint tracking control of ships on a straight path is achieved.

II. PROBLEM FORMULATION AND MATHEMATICAL PRELIMINARIES

A. Nonlinear Straight-path Tracking Model of Ships

For waypoint tracking problem only the horizontal plane ship motion is used. When a ship moves on a straight line at a constant cruising speed, the surge speed $u \gg 0$, the sway speed $v \approx 0$, thus the ship cruise speed $U = \sqrt{u^2+v^2} \approx u$. Similar to [5], choosing the Earth-fixed coordinate system such that its origin is at the previous waypoint, the x-axis points towards the next waypoint, and the cross-track error equals the sway position y of the ship (see Fig.1).

Now consider the following nonlinear ship straight-line motion equation ([13])

$$\begin{cases} \dot{y} = U\sin(\psi) \\ \dot{\psi} = r \\ \dot{r} = a_1 r + a_2 r^3 + b\delta + w \end{cases} \tag{1}$$

where y, ψ, r and U denote the sway displacement (cross-track error), heading angle, yaw rate and cruise speed re-

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spectively. $a_1 = -1/T$, $a_2 = -\alpha/T$, $b = K/T$. In this paper, we assume that U, T, K and α are unknown but constant. δ denotes the control rudder angle; $w = f_A + f_W$ denotes equivalent external perturbations induced by wave and wind, where f_A represents steady wind equivalent disturbance, and f_W depicts regular wave equivalent disturbance effect. In light of [16] and [17], f_A and f_W are characterized as

$$f_A = \frac{\rho_a}{\rho}\frac{A_s}{Ld}\left(\frac{-C_{Na}Y_v' + C_{Ya}N_v'}{-N_v'Y_\delta' + Y_v'N_\delta'}\right)\left(\frac{U_a}{U}\right)^2,$$

$$\begin{aligned} f_W =& \frac{1}{2U^2d}\left(\frac{-Y_v'C_{Nw}\cos(\omega_e t) + N_v'C_{Yw}\sin(\omega_e t)}{-N_v'Y_\delta' + Y_v'N_\delta'}\right)h_W^2 \\ =& D_1\cos(\omega_e t) + D_2\sin(\omega_e t). \end{aligned}$$

Refer to [16] and [17] for the exact meaning with respect to the coefficients and variables respectively.

***Assumption 1*:** The high-frequency gain b and its sign are completely unknown.

Remark 1: In practice, the sign of b is determined via the ship test or the trial-and-error way. In this sense, the algorithm to be developed later can ease the controller design .

***Assumption 2*:** The disturbance w is slowly time-varying, bounded, and its exact bound is unknown. But it satisfies

$$|w| \le \lambda\phi(x), \tag{2}$$

where λ is an unknown positive constant, and ϕ is a known nonnegative smooth function.

In this paper, we aim at developing a robust adaptive controller for system (1), such that the cross-track error y, yaw angle ψ and yaw rate r can be stabilized respectively.

B. Nussbaum Gain Technique

In this paper, Nussbaum gain ([11]) is employed to cope with the unknown control gain b with an unknown sign .

Lemma 1([10]): Let $V(\cdot)$ and $\kappa(\cdot)$ be smooth functions defined on $[0,t_f)$ with $V(t) \ge 0$,$\forall t \in [0,t_f)$, $N(\cdot)$ be an even smooth Nussbaum-type function, and b be a nonzero constant. If the following inequality holds:

$$\begin{aligned} V(t) \le C_0 + e^{-c_1 t}\int_0^t g(x(\tau))N(\kappa)\dot{\kappa}e^{c_1 t}d\tau \\ + e^{-c_1 t}\int_0^t \dot{\kappa}e^{c_1 t}d\tau, \forall t \in [0,t_f) \end{aligned} \tag{3}$$

where C_0 represents some suitable constant, then $V(t)$, $\kappa(t)$ and $\int_0^t (bN(\kappa(\tau)) + 1)\dot{\kappa}(\tau)d\tau$ must be bounded in $[0,t_f)$.

***Remark 2*:** According to Proposition 2 in Ryan[15], if the solutions to the closed-loop system exist, then $t_f = \infty$. So the boundedness result in Lemma 1 can be extended to globally uniformly ultimately bounded(GUUB).

Throughout this paper, an even Nussbaum function $N(\kappa) = \exp(\kappa^2)\cos((\pi/2)\kappa)$ is used.

III. DESIGN PROCEDURE AND STABILITY ANALYSIS

A. Minimum-phase Property in Our Interested System

Define the following coordinate transformation:

$$x_1 = \psi + \arcsin\left(\frac{ky}{\sqrt{1 + (ky)^2}}\right) \tag{4}$$

where k is a positive constant. Note that the convergence of x_1 and y to zero implies that of ψ.

Then the system (1) can be rewritten as

$$\left\{\begin{array}{l} \dot{x}_1 = U\frac{k\sin\psi}{1+(ky)^2} + x_2 \\ \dot{x}_2 = a_1x_2 + a_2x_2^3 + b\delta + w \\ \dot{y} = U\sin\left(x_1 - \arcsin\left(\frac{ky}{\sqrt{1+(ky)^2}}\right)\right) \\ \zeta = x_1 \end{array}\right. \tag{5}$$

where $x_2 = r$, $\zeta = x_1$ is the desired system output. Now notice that the stabilization of (1) becomes that of (5) via the global transformation (4). In order to ease the controller design of (5), we address the following proposition:

Proposition 1 (Theorem 1, [14]): For system (5) with $w = 0$, if x_1 is globally asymptotically stabilized by the control input δ, then the track error y is globally asymptotically stable (GAS), consequently, the system (5) is a minimum-phase system with a stable zero dynamics.

Proof : See the proof of Theorem 1 in [14].

Since the $\dot{y}$-subsystem of (5) is zero-dynamics internal stable, by dropping the $\dot{y}$-subsystem, the system (5) can be simplified and reduced to the following system

$$\left\{\begin{array}{l} \dot{x}_1 = x_2 + \theta^T f_1 \\ \dot{x}_2 = b\delta + \theta^T f_2 + w \\ \zeta = x_1 \end{array}\right. . \tag{6}$$

where $\theta = [\theta_1, \theta_2, \theta_3]^T = [U, a_1, a_2]^T$, $f_1 = \left[k\sin\psi\Big/\left(1 + (ky)^2\right), 0, 0\right]^T$, $f_2 = \left[0, x_2, x_2^3\right]^T$.

B. Robust Adaptive Design Process

The structure of system (6) suggests us to design the controller in two stages by applying the cancellation backstepping approach.

***Step 1*:** Let $z_1 = \zeta = x_1$, $z_2 = x_2 - \alpha_1$. The derivative of z_1 is

$$\dot{z}_1 = z_2 + \alpha_1 + \theta^T f_1 \tag{7}$$

To stabilize (7), we define the first Lyapunov function as

$$V_1 = \frac{1}{2} z_1^2 + \frac{1}{2} \tilde{\theta}^T \Gamma^{-1} \tilde{\theta} \quad , \tag{8}$$

where $\tilde{\theta} = \theta - \hat{\theta}$ is parameter error, $\tilde{\theta}$ is parameter estimate of θ, $\Gamma > 0$ is the adaptation gain matrix.

The derivative of V_1 along the solutions of (7) is

$$\dot{V}_1 = z_1 \left(z_2 + \alpha_1 + \hat{\theta}^T f_1 \right) - \tilde{\theta}^T \Gamma^{-1} \left(\dot{\hat{\theta}} - \Gamma f_1 z_1 \right). \tag{9}$$

Now select the stabilizing function as

$$\alpha_1 = -c_1 z_1 - \hat{\theta}^T f_1 \quad , \tag{10}$$

where $c_1 > 0$ is a design parameter.

Since x_2 is not the actual control, we do not use $\dot{\hat{\theta}} = \Gamma \tau_1$ as an update law to eliminate $\tilde{\theta}$ from $\dot{V}_1$ in this step. Instead, we retain τ_1 as our tuning function, which is defined as

$$\tau_1 = f_1 z_1 \quad ,$$

and tolerate the presence of $\tilde{\theta}$ in V_1 :

$$\dot{V}_1 = -c_1 z_1^2 + z_1 z_2 - \tilde{\theta}^T \Gamma^{-1} \left(\dot{\hat{\theta}} - \Gamma \tau_1 \right) \tag{11}$$

The second term $z_1 z_2$ in $\dot{V}_1$ will be cancelled at the next step. Now we can obtain the z_1-subsystem as

$$\dot{z}_1 = -c_1 z_1 + z_2 + \tilde{\theta}^T f_1 \tag{12}$$

***Step 2*:** At this step, the actual control input u appears in the $\dot{z}_2$-subsystem

$$\begin{aligned} \dot{z}_2 = & \left(b\delta + \theta^T f_2 + w \right) - \frac{\partial \alpha_1}{\partial x_1} \left(x_2 + \theta^T f_1 \right) \\ & - \frac{\partial \alpha_1}{\partial \hat{\theta}} \dot{\hat{\theta}} - \frac{\partial \alpha_1}{\partial \psi} \dot{\psi} - \frac{\partial \alpha_1}{\partial y} \dot{y}. \end{aligned} \tag{13}$$

Select the augmented Lyapunov function as

$$V_2 = V_1 + \frac{1}{2} z_2^2 + \frac{1}{2\gamma} \tilde{\lambda}^2 \quad , \tag{14}$$

where $\gamma > 0$ is a design parameter to be selected later. In view of (11), (13) and (2), the derivative of V_2 is

$$\begin{aligned} \dot{V}_2 = & \dot{V}_1 + z_2 \dot{z}_2 - \tilde{\lambda}^T \gamma^{-1} \dot{\hat{\lambda}} \\ \le & -c_1 z_1^2 - \tilde{\theta}^T \Gamma^{-1} \left(\dot{\hat{\theta}} - \Gamma \tau_1 \right) + z_1 z_2 \\ & + z_2 \left(b\delta + \theta^T f_2 + \lambda \phi - \tfrac{\partial \alpha_1}{\partial \hat{\theta}} \dot{\hat{\theta}} \right. \\ & \left. - \tfrac{\partial \alpha_1}{\partial x_1} \left(x_2 + \theta^T f_1 \right) \right) - \tilde{\lambda}^T \gamma^{-1} \dot{\hat{\lambda}} \\ \le & -c_1 z_1^2 - \tilde{\theta}^T \Gamma^{-1} \left(\dot{\hat{\theta}} - \Gamma \left(\tau_1 + \left(f_2 - \tfrac{\partial \alpha_1}{\partial x_1} f_1 \right) \right) \right) \\ & + z_2 \left(b\delta + \hat{\theta}^T f_2 + \upsilon + \hat{\lambda} \phi \tanh \left(\tfrac{z_2 \phi}{\varepsilon} \right) \right) \\ & + \lambda \left(|z_2 \phi| - z_2 \phi \tanh \left(\tfrac{z_2 \phi}{\varepsilon} \right) \right) \\ & - \tilde{\lambda}^T \left(\dot{\hat{\lambda}} - \gamma z_2 \phi \tanh \left(\tfrac{z_2 \phi}{\varepsilon} \right) \right) \end{aligned} \tag{15}$$

where $\upsilon = z_1 - \frac{\partial \alpha_1}{\partial x_1} \left(x_2 + \hat{\theta}^T f_1 \right) - \frac{\partial \alpha_1}{\partial \hat{\theta}} \dot{\hat{\theta}} - \frac{\partial \alpha_1}{\partial \psi} \dot{\psi} - \frac{\partial \alpha_1}{\partial y} \dot{y}$ is a compensating input defined to cancel the relevant items from $\dot{V}_1$.

Now we are in position to design the controller δ and parameter update laws $\dot{\hat{\theta}}$ and $\dot{\hat{\lambda}}$.

First, we define the controller δ as follows

$$\delta = N(\kappa)\beta, \tag{16}$$

$$\beta = c_2 z_2 + \hat{\theta}^T f_2 + \upsilon + \hat{\lambda} \phi \tanh \left(\frac{z_2 \phi}{\varepsilon} \right) \tag{17}$$

$$\dot{\kappa} = \beta z_2, \tag{18}$$

$$N(\kappa) = e^{\kappa^2} \cos \left((\pi/2) \kappa \right), \tag{19}$$

For parameter adaptation, in order to prevent parameter drifts in eliminating $\tilde{\theta}$ and $\tilde{\lambda}$ in $\dot{V}_2$, we present the following adaptive laws based upon a variation of σ-modification:

$$\dot{\hat{\theta}} = \Gamma \left[\tau_1 + \left(f_2 - \frac{\partial \alpha_1}{\partial x_1} f_1 \right) z_2 - \sigma_\theta \left(\hat{\theta} - \theta^0 \right) \right] \tag{20}$$

$$\dot{\hat{\lambda}} = \gamma z_2 \phi \tanh \left(\frac{z_2 \phi}{\varepsilon} \right) - \gamma \sigma_\lambda \left(\hat{\lambda} - \lambda^0 \right) \tag{21}$$

where σ_θ, σ_λ, θ^0, λ^0 are positive design constants.

Remark 3: In order to enhance the robustness of our proposed controller against the external disturbances, we choose $\lambda = |f_A| + |D_1| + |D_2|$, $\phi = 1$.

By instituting (16)-(21) into (15), then (15) becomes

$$\begin{aligned} \dot{V}_2 \le & -c_1 z_1^2 - c_2 z_2^2 - \tfrac{1}{2} \sigma_{\theta 1} \left| \tilde{\theta} \right|^2 - \tfrac{1}{2} \sigma_\lambda \left| \tilde{\lambda} \right|^2 \\ & + (bN(\kappa) + 1) \dot{\kappa} + \delta_2 \\ \le & -cV_2 + (bN(\kappa) + 1) \dot{\kappa} + \eta \end{aligned} \tag{22}$$

where $\eta = \frac{1}{2}\sigma_\theta \left|\theta - \theta^0\right|^2 + \frac{1}{2}\sigma_\lambda \left|\lambda - \lambda^0\right|^2 + 0.2785\hat{\lambda}\varepsilon$, $c :=$ $\min\left\{c_1, c_2, \frac{\sigma_\theta}{\lambda_{\max}\left(\Gamma^{-1}\right)}, \sigma_\lambda \gamma\right\}$. In the above analysis, the facts $\tilde{\theta}^T\left(\hat{\theta} - \theta_0\right) = \frac{1}{2}\left|\tilde{\theta}\right|^2 + \frac{1}{2}\left|\hat{\theta} - \theta_0\right|^2 - \frac{1}{2}\left|\theta - \theta_0\right|^2$ and $0 \le |x| - x\tanh\left(\frac{x}{\varepsilon}\right) \le 0.2785\varepsilon, \varepsilon > 0, x \in R$ are used.

Let $\rho = \delta_2/c$, upon multiplication of (22) by e^{ct}, it becomes

$$\frac{d}{dt}\left(V_2(t)e^{ct}\right) \le \eta e^{ct} + bN(\kappa)\dot{\kappa}e^{ct} + \dot{\kappa}e^{ct} \quad . \tag{23}$$

Integrating (23) over $[0, t]$, we have

$$\begin{aligned} 0 &\le V_2(t) \\ &\le \rho + [V_2(0) - \rho]e^{-ct} \\ &\quad + e^{-ct}\int_0^t (bN(\kappa) + 1)e^{c\tau}\dot{\kappa}d\tau \\ &\le \rho + V_2(0) + e^{-ct}\int_0^t bN(\kappa)\dot{\kappa}e^{c\tau}d\tau \\ &\quad + e^{-ct}\int_0^t \dot{\kappa}e^{c\tau}d\tau \end{aligned} \tag{24}$$

By choosing $C_0 = \rho + V_2(0)$, and from Lemma 1 and Remark 2, it can be concluded that $V_2(t)$, κ, consequently z_2, $\hat{\theta}$, $\hat{\lambda}$ and the control input δ, as well as z_1 and V_1 are all GUUB. Consequently x_1 and x_2 are GUUB.

Remark 4: Because the virtual control gain coefficient of x_2 in the $\dot{x}_1$-subsystem is 1, it is not necessary to use Nussbaum gain technique in Step 1. Consequently we can use the cancelled backstepping approach to design the control law in Step 2, also to avoid overparametrization, instead of the decoupled backstepping approach as in [9] and [10].

Theorem 1: For the closed-loop adaptive system consisted of system (6) and the adaptive laws (20) and (21), the state feedback law (16) renders its solutions globally uniformly ultimately bounded. Moreover,the following properties can be guaranteed:

i) all the signals and solutions in the closed-loop system remain GUUB,

ii) for any given $\varepsilon^* > \sqrt{2\rho}$, there exists a $T > 0$, such that $|z(t)| \le \varepsilon^*$ for all $t \ge T$. Furthermore, ε^* can be made as small as desired by an appropriate choice of the design parameters such that the output z_1 satisfies the property of $\lim\limits_{t\to\infty}|z_1(t)| \le \varepsilon^*$.

Proof: The proof can be easily completed by the previous design procedures from Step 1 to Step 2. Since the system output $\zeta = x_1(t) = z_1(t)$, from the definition of V_1 and (12), the property (ii) can be easily obtained. Thus, by appropriately choosing the design constants, the regulation of z_1 to any prescribed accuracy can be achieved while keeping the boundedness of all signals and states involved.

According to Proposition 1, the track error y in system (5) is regulated. And in view of (4), ψ is also regulated. In turn, the system (1) is regulated.

IV. SIMULATION RESULTS

In this section, simulation results are based on an ocean-going training vessel YULONG, whose length L is 126 m, breadth B is 20.8 m, full-load draft d is 8.0 m, C_b is 0.681, and nominal speed U 7 m/s, By calculation we obtain K =0.4963, T =208.91, α =30. The design parameters were chosen as $\sigma_\theta = [10, 10, 30]^T$, $\Gamma = [0.05, 0.005, 0.005]^T$, $k = 0.005$, $c_1 = 0.01$, $c_2 = 15$, $\varepsilon = 0.1$, $\gamma = 0.1$. The initial condition is set to be $y_0 = 500$ m, $\psi_0 = 10^0$, $\kappa(0) = 0.5*\pi$, $\hat{\theta}_1(0) = \hat{\theta}_2(0) = \hat{\theta}_3(0) = \hat{\lambda}(0) = 0$ and [$x(0)$, $y(0)$, $\psi(0)$]= [10m, 500m, 10^0] respectively.

Simulation results using Matlab Simulink illustrate the properties of the proposed algorithm by Figs. 2-9, where χ is the angle of wave direction, α_R is the angle of the wind to the ship .

Fig.2 shows the evolution of waypoint tracking of a ship when wind speed $V_a = 12$ [m/s]. Fig.3∼9 illustrate the boundedness of the state variables and signals involved respectively. In addition, it can be seen that, (1) to compensate for the external perturbations induced by wind and waves, control rudder angle have to varies around a certain value (e.g. -10^0 under $V_a = 12$ (m/s)) while the cross-track error converges close to the neighborhood of the origin, (2) the control effort increases along with the increases of both the relative wind speed V_a and the angle α_R shifting to the beam of ships. The control-saturation phenomenon implies that "hard rudder" should be used at the beginning due to a large initial cross-track error and the presence of external disturbances induced by wind and waves. From above illustrations, we can conclude that robust adaptive way-point tracking control of ships is indeed able to be achieved by our proposed algorithm.

V. CONCLUSIONS

In this paper, we have explored a robust adaptive design method for ship straight-line tracking control problemThe algorithm was developed by combing the powerful backstepping approach and Nussbaum-type gain technique, such that all signals and states in the closed-loop are GUUB. Consequently, globally robust adaptive way-point tracking control of ships can be indeed achieved.

VI. ACKNOWLEDGMENTS

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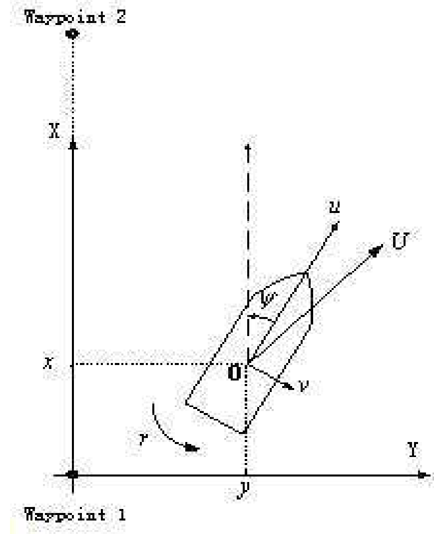

Fig. 1. Ship motion coordinate system.

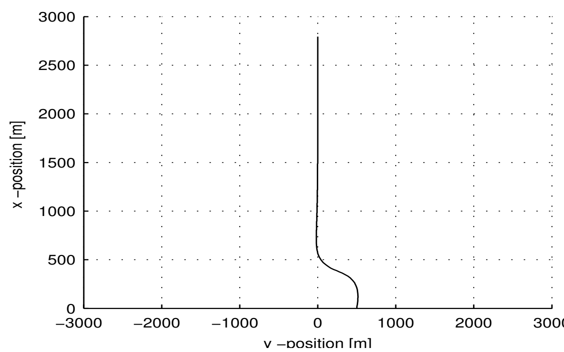

Fig. 2. The trajectory in the *xy*-plane [m] when $V_a = 12[m/s]$.

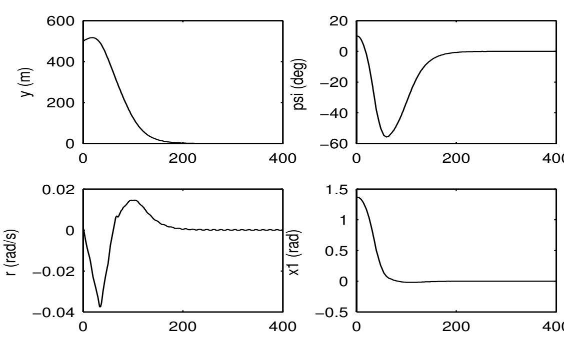

Fig. 3. Time response of cross-track error y[m], heading angle ψ[deg] ,yaw rate r [rad/s] and redefinition output x_1 [rad] when $V_a = 12[m/s]$ and $\alpha_R = \chi = \frac{\pi}{6}$.

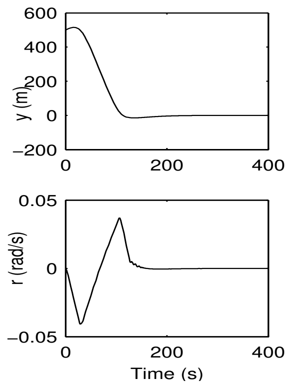

Fig. 4. Time response of cross-track error y[m], heading angle ψ[deg] , yaw rate r [rad/s] and redefinition output x_1 [rad] when $V_a = 8[m/s]$ and $\alpha_R = \chi = \frac{\pi}{2}$.

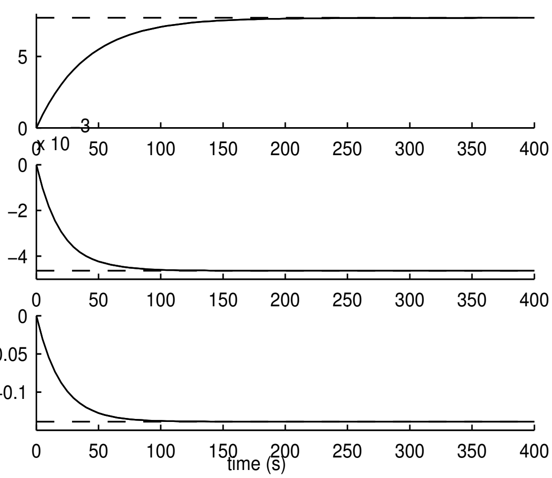

Fig. 5. Adaptation history of $\hat{\theta}_1$ [m/s] (up), $\hat{\theta}_2$ [s^{-1}] (middle), and $\hat{\theta}_3$ [s^{-1}] (down).

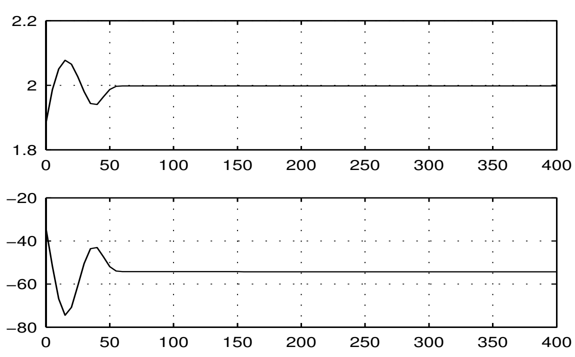

Fig. 6. Adapting parameter κ (Up) and Nussbaum gain $N(\kappa)$ (Down) when $V_a = 8[m/s]$ and $\alpha_R = \chi = \frac{\pi}{6}$.

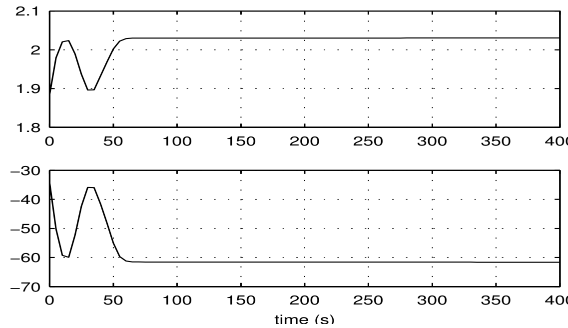

Fig. 7. Adapting parameter κ (Up) and Nussbaum gain $N(\kappa)$ (Down) when $V_a = 12[m/s]$ and $\alpha_R = \chi = \frac{\pi}{6}$.

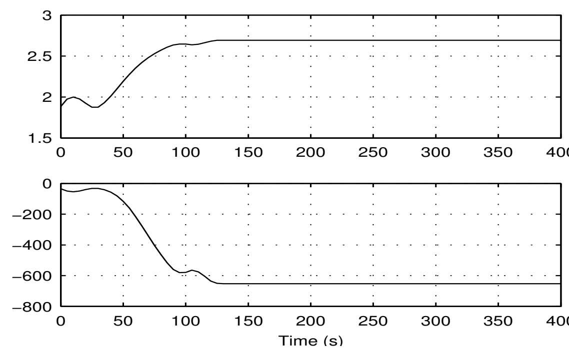

Fig. 8. Adapting parameter κ (Up) and Nussbaum gain $N(\kappa)$ (Down) when $V_a = 8[m/s]$ and $\alpha_R = \chi = \frac{\pi}{2}$.

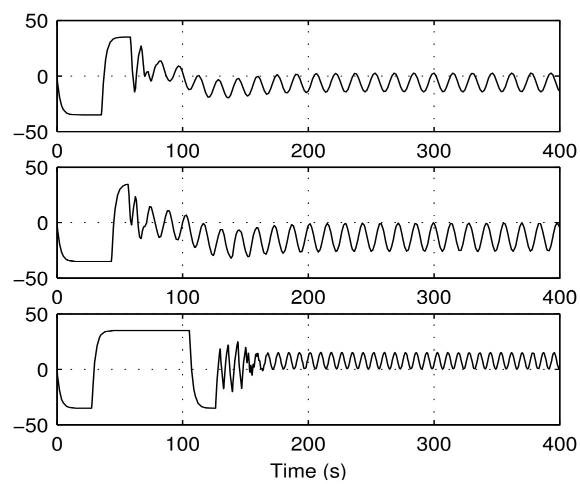

Fig. 9. Control effort δ[deg] under three simulation conditions: Up: $V_a = 8[m/s]$ and $\alpha_R = \chi = \frac{\pi}{6}$; Middle: $V_a = 12[m/s]$ and $\alpha_R = \chi = \frac{\pi}{6}$; Down: $V_a = 8[m/s]$ and $\alpha_R = \chi = \frac{\pi}{2}$